POSSIBLE FLUCTUATIONS IN THE DELAYED NEUTRON YIELDS IN THE RESONANCE REGION OF U-235

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Abstract - An evaluation of the delayed neutron yield in the resonance region of U-235 was made on the basis of multimodal interpretation of local fluctuations of fragment mass and kinetic energy distributions at resonances observed in experiments performed at Geel. In contrast to the evaluation adopted in JEF-2.2, the calculated delayed neutron yield showed local dips at resonances.

INTRODUCTION

It is known that the delayed neutron (DN) yield remains almost constant in the energy range below 4 MeV. However, it has been suggested by reactor physicists (Kaneko *et al.*, 1988) that the DN yield in the near-thermal region might be smaller than the constant value. In fact, some of the experimental data on DN yield in the lower end of the region tends to be lower than the plateau value (see Fig.1). Reflecting these facts, evaluated data of the absolute DN yield for U-235 in JENDL-3.2 have a slight positive slope in the energy region concerned, and JEF-2.2 evaluation has some structures in the eV-region. (In contrast, ENDF/B-VI adopted a constant value. See Fig.2.) However, physical reason for the decrease in the lower end of the region has not been clear so far, because, according to conventional theories of fission, it was hard to consider that the precursor yields changed significantly in such a small energy range.

This report proposes a possible interpretation for the decrease, on the basis of multimodal analysis of fragment mass distribution in the resolved resonance region of U-235.

FISSION MODE FLUCTUATIONS AT RESONANCES

Hambsch *et al.* (1989) observed a difference in the fission fragment mass distributions from resonance-to-resonance for U-235, which was correlated with fluctuations of the reaction Q-value and also with the total kinetic energy averaged over all fragments. These data were analyzed in terms of multimodal fission model proposed by Brosa *et al.*, (1990) and it was found that the mode branching ratios (w_{S1}, w_{S2}, *etc.*) differ from resonance-to-resonance, the observed changes of the ratios $(w_{S1}/w_{S2})_{res}/(w_{S1}/w_{S2})_{th}$ ranging

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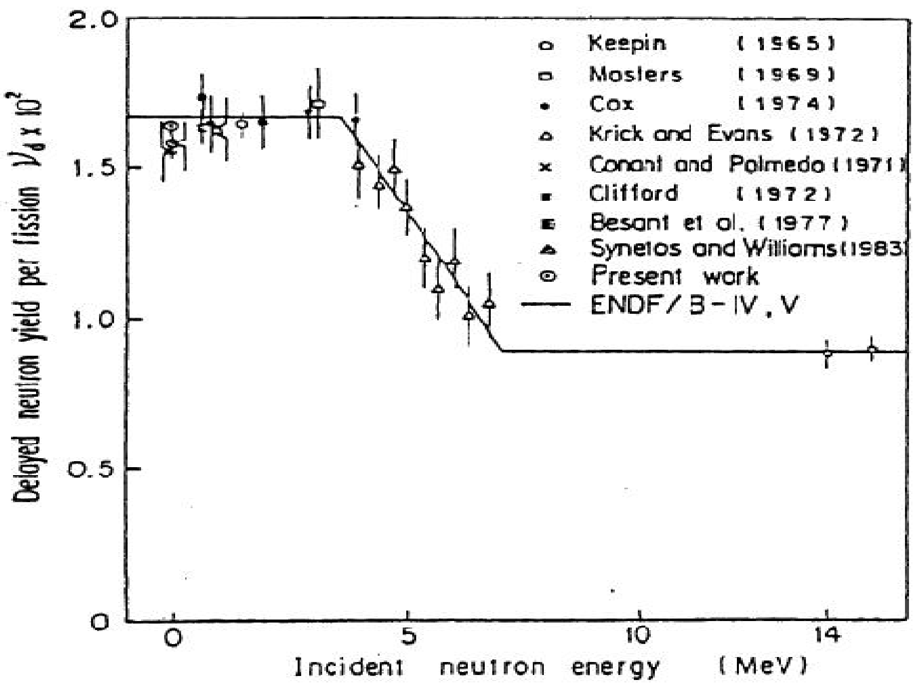

Fig.1 Experimental and evaluated data of delayed neutron yield for U-235 (taken from Kaneko *et al.*, 1988).

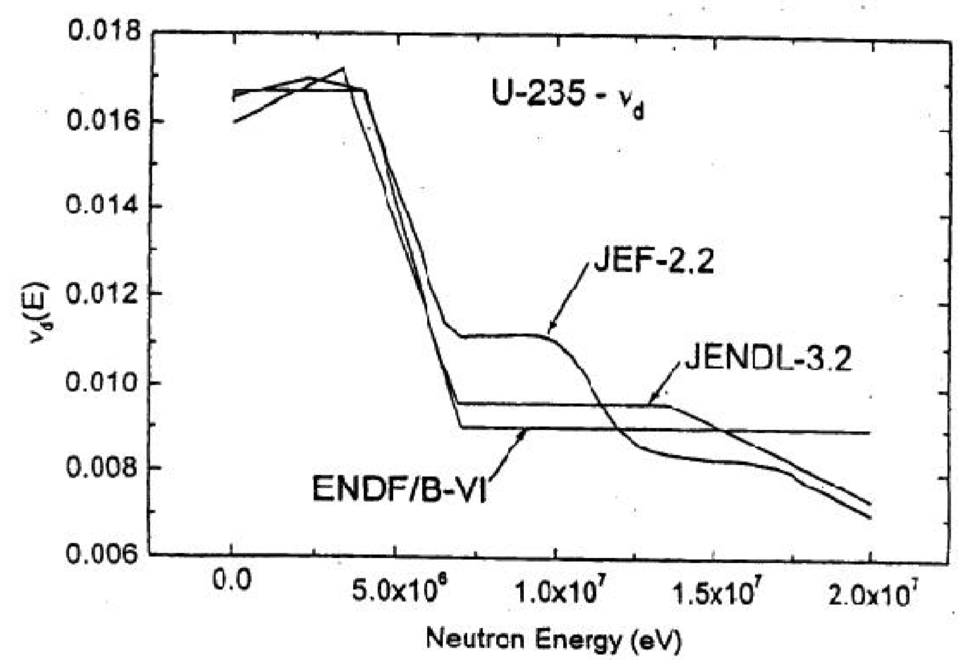

Fig.2 Comparison of evaluated DN yield data for U-235 in JENDL-3.2, JEF-2.2 and ENDF/B-VI.

up to 20% (the subscript S1, S2 refer to Standard-1 and Standard-2 mode, respectively). This amounts to a decrease of fission yields of the outside wings (A = 84–96, 140–152) and an increase of the inside wings (A = 96–108, 128–140) of the mass distribution (see Fig.3).

On the other hand, precursors of delayed neutrons lie in the region where a nucleus has a few excessive neutrons just outside of the closed shell, because such a nucleus has a higher neutron emission probability after beta-decay due to the lower neutron binding energy of the DN-emitter nucleus. These precursor regions are denoted in Fig.3 with bold horizontal line segments. It can readily be seen that these regions overlap with the regions where substantial changes of mass yield are observed in the resonance-neutron fission. This implies that the yields of DN precursors fluctuate in the resonance region, resulting in local variation of the DN yield. In order to verify this reasoning, estimation of possible changes in the DN yield was made using the data of Hambsch *et al.* (1989) as the basis.

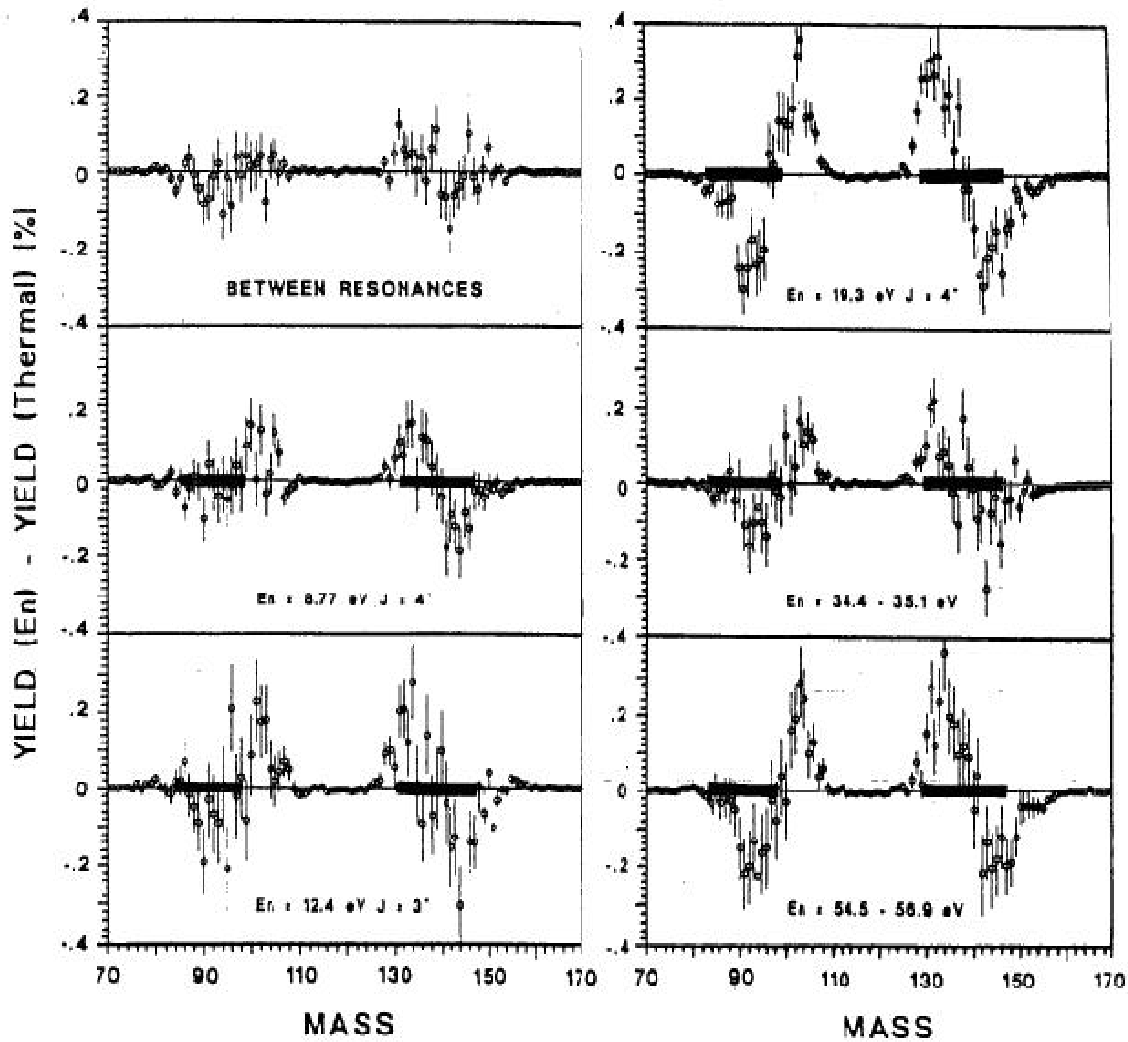

Fig. 3 Fragment yield differences at resonances with respect to the thermal values. (After Hambsch *et al.* (1989). The bold horizontal line segments, indicating the precursor regions, were added by the present authors.)

METHOD

The total DN yield was calculated using the summation method.

$$\nu_d = \Sigma\, Y_i P_{ni} \quad , \tag{1}$$

where Y_i is the fission yield and P_{ni} is the neutron emission probability of a precursor *i*. The fission yield Y_i was calculated by using the five-Gaussian representation with parameters given by Hambsch *et al.*, together with the data of Nishio *et al.* (1995) on the prompt neutron multiplicity $\nu_p(A^*)$ as a function of the pre-neutron-emission mass of the fragments. Fragment charge distribution of Gaussian shape with the standard deviation σ =0.56 and the most probable charge

$$Z_p = Z_{UCD} \pm 0.5 \quad , \tag{2}$$

was used to obtain the independent fission yields, where Z_{UCD} is the charge predicted with the unchanged charge distribution (UCD) hypothesis. The even-odd effect of the proton number on the fission yield, defined by

$$X = (Z_e - Z_o)/(Z_e + Z_o) \quad , \tag{3}$$

was considered, using the formula proposed by the present author,

$$X = -\,0.1033 + 0.6907/\,(Z^2/A - 33.8486) \quad . \tag{4}$$

Two sets of data for the neutron emission probability were used: 1) the set of Mann *et al.* (1984), comprised of 79 precursors, and 2) the set of Wahl (1988), comprised of 271 precursors.

RESULTS

The difference of the DN yield at 10.18 eV-resonance with respect to the thermal value, as a function of precursor mass, are shown in Figs.4a and b where Mann's and Wahl's P_n-data were used, respectively. In the heavy fragment (HF) region, a structure similar to Fig.3 is observed, which means that positive and negative contributions almost cancel out. In the light fragment (LF) region, however, the positive contribution is much less than the negative contribution, thus resulting in negative total value in this region. The same applies to other resonances, except 4.85, 38.41 and 81.9-86.2eV resonances where the opposite tendency is observed in mode branching ratios. Therefore the total DN yield at resonances is decreased compared with the thermal value, except for the three cases. This tendency is more emphasized for Fig.4b, because much more precursors are considered in Wahl's data set.

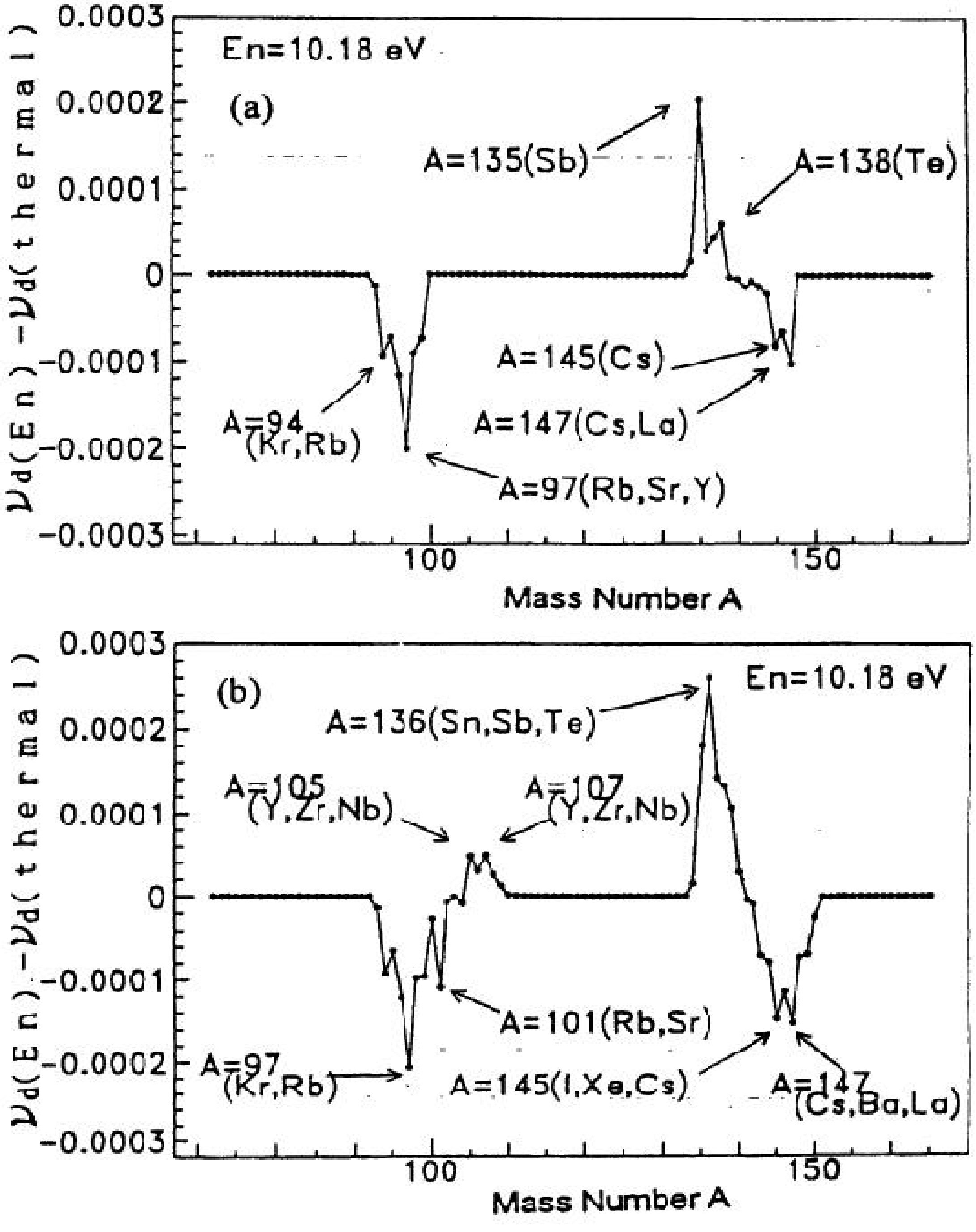

Fig.4. The difference of the DN yield at 10.18 eV-resonance with respect to thermal values as a function of precursor mass, calculated by using Mann's (a) and Wahl's data set (b).

The relative variation of the DN yield $\nu_d(E)/\nu_d(\text{thermal})$ simulated using the resonance parameters in Mughabghab (1984) is shown in Fig.5. The degree of decrease differs from one resonance to another, the maximum decrease being about 2.3% in the region less than 100 eV. The effect of these dips in $\nu_d(E)$

on reactor physics will be amplified many times more than this value due to locally enhanced fission cross section at the resonances. Two comments should be added here.

First, the present result is only a preliminary one. The fragment charge distribution used in this work is just a rough approximation. Since the precursor nuclides lie in the tail region of the charge distribution curve, a slight change in the most probable charge Z_p, given by Eq. (2), and the standard deviation σ will change the fission yield considerably. Mass-dependent deviation of Z_p from Eq. (2) and possible fluctuation of σ , as was reported in Wahl (1988), should be included. Refinement is required also for even-odd effect on fission yield; its dependence on the fragment mass and on the excitation energy should further be investigated.

And second, Figure 5 reminds us of the local dips at resonances observed in the average *prompt* neutron multiplicity $\nu_p(E)$ in ^{239}Pu. Fort *et al.* (1988) analyzed these dips in terms of spin effect and $(n, \gamma f)$-effect, and their result was reflected in JEF-2.2 file. They applied the model of Lendel *et al.* (1986), which took into account the $\nu_p(E)$-dependence of the most probable charge, to evaluate the DN yield at resonances. This resulted in prominent local 'spikes' in the DN yield $\nu_d(E)$ at resonances where prompt neutron multiplicity shows dips, as can be seen in Fig.6, and consequently more pronounced peaks in the relative DN fraction β (=ν_d / ν_p) at resonances in JEF-2.2 data. In a word, the two quantities $\nu_d(E)$ and $\nu_p(E)$ are *anti-correlated* in this methodology.

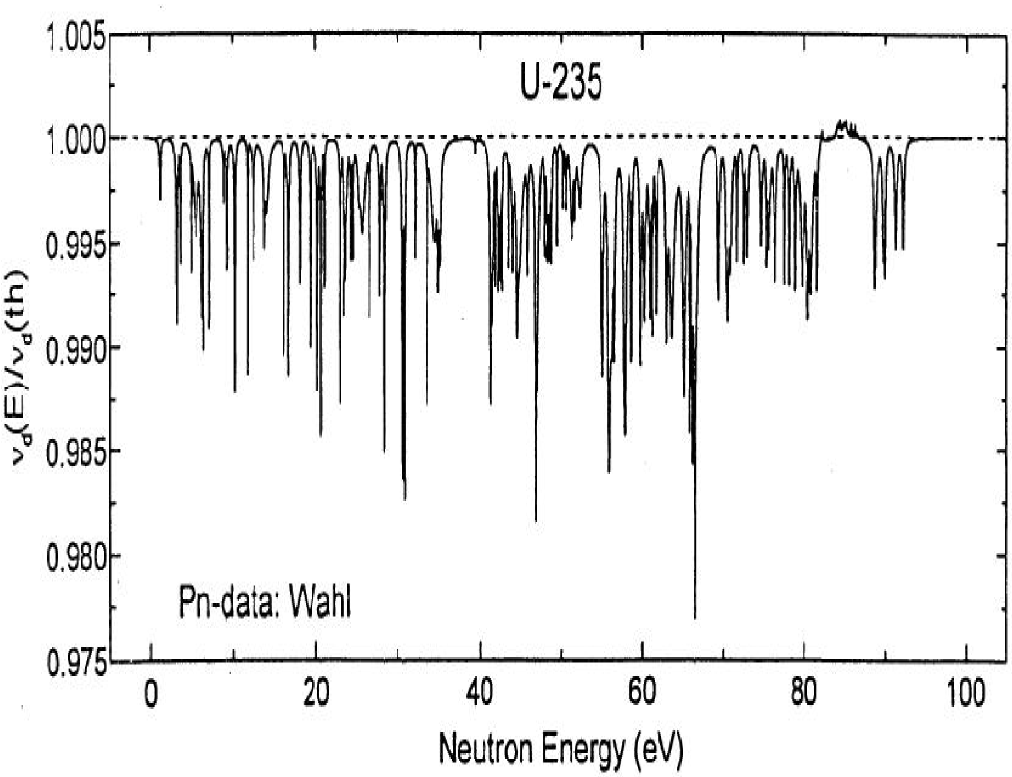

Fig.5. The relative variation of the DN yield $\nu_d(E)$/ ν_d(thermal) simulated using the resonance parameters in Mughabghab (1988).

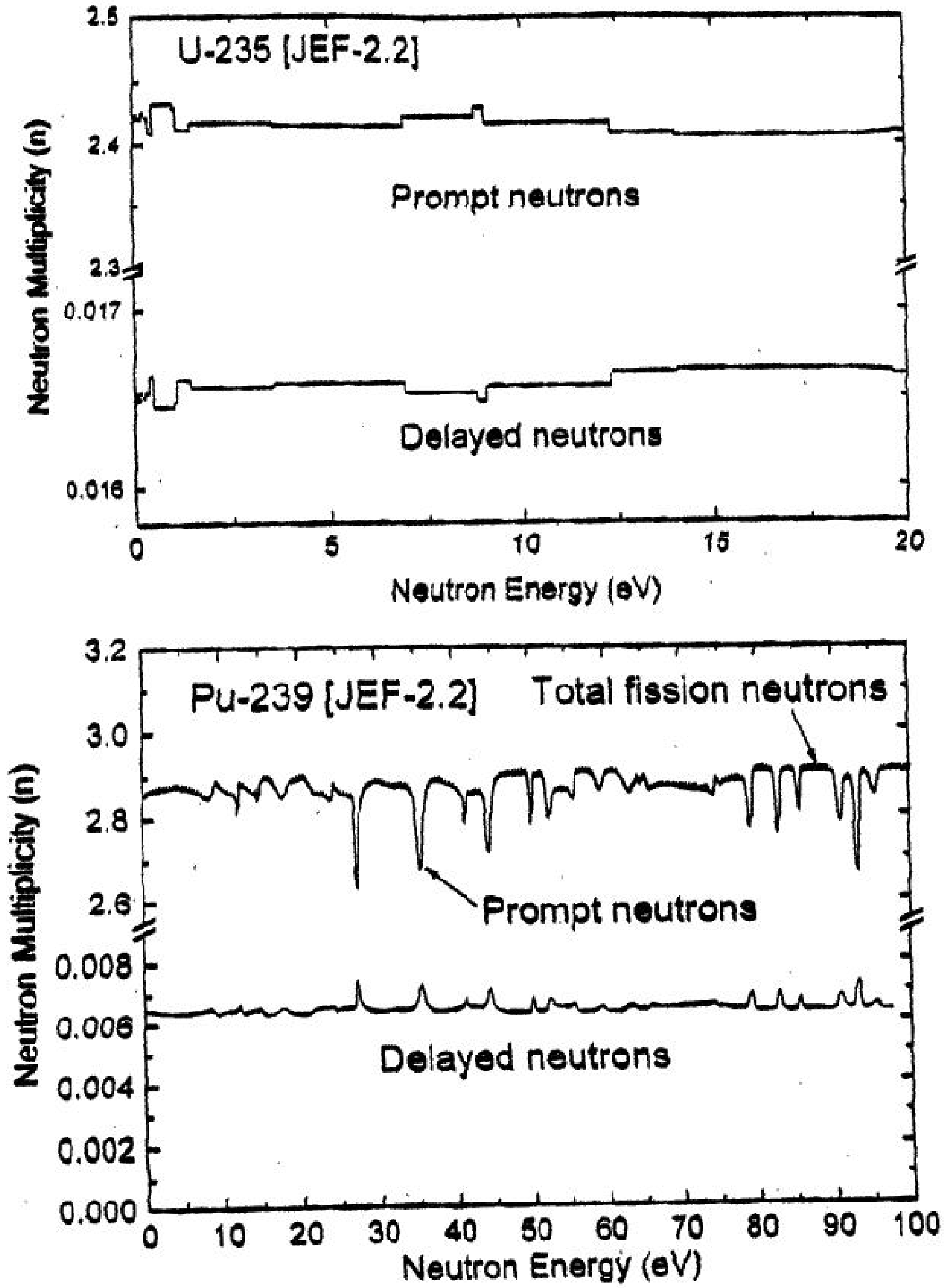

Fig.6. Evaluated data in JEF-2.2 of the prompt and delayed neutron yields in the resonance region of ^{235}U (a) and ^{239}Pu (b).

In contrast, the present analysis predicts a *positive correlation* between $\nu_p(E)$ and $\nu_d(E)$. For lack of experimental data on the DN yield at individual resonance, it is not possible at present to judge if there is a positive or negative correlation between the two quantities. However, the authors believe that the present result is probable for two reasons. Although there is no direct experimental evidence for local decrease of $\nu_d(E)$ at resonances, there is evidence that, at resonances, the fission yield decreases just in the fragment mass region where important precursors exist. Furthermore, local dips in the DN yield in the resonance region give a possible explanation to the slight decrease of $\nu_d(E)$ in the near-thermal region for which physical ground was not clear thus far.

Hambsch *et al.*(1989) pointed out that the dips in ν_p are due to local changes in mode branching ratios w_i and that these changes are not correlated with the spin of the resonance. This interpretation is different from the previous one (Fort *et al.*, 1988). A new approach to a unified treatment of $\nu_p(E)$ and $\nu_d(E)$ on the basis of the multimodal fission model is under way.

CONCLUSIONS

Detailed measurements of the fragment mass and kinetic energy distributions and their analyses in the 'language' of multimodal fission model performed during the last decade revealed many interesting features of the fission process. These studies have brought a new insight into the interpretation of variation of the DN yield in the resonance region. However, one should note that Hambsch's measurement is on ^{235}U and Fort's evaluation mainly concerns ^{239}Pu. It is thus highly desirable that measurements of fluctuation in the fragment mass distribution in the resonance region of ^{239}Pu will be made with high precision. Consistent simultaneous evaluation of prompt and delayed neutron multiplicity in terms of the multimodal fission model on the same nucleus would help to solve the problem.

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